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A Refined and Less Conservative Day-of-Launch Atmospheric Flight Loads Analysis Approach

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Abstract

A day-of-launch atmospheric flight loads analysis approach that reduces conservatism by better defining the components of flight loads that have to be treated statistically and those that can be established with measured wind profiles just prior to launch is described. The approach introduces the concept of removing from measured day-of-launch winds the rapidly-varying features, and only using the more slowly-changing components in the load calculations performed just prior to launch. The proposed approach takes advantage of two recent developments. The first development defines the spectral boundary, as a function of time, between wind components that can be considered slowly varying and those that change rapidly and, hence, have to be addressed statistically. The second development provides an approach for calculating gust loads due only to the turbulent component of the winds, and thus, eliminates the need to include these wind components in the load calculations performed just prior to launch.

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Nomenclature

T = lack-of-wind persistence time (minutes)

1. Introduction

During atmospheric flight, launch vehicles and their payloads will experience severe structural loading.[1-12] If a launch vehicle and its payload are sufficiently robust, it can be demonstrated statistically that reliability requirements for flight loads can be met without performing load placard calculations on the day of launch. However, many launch vehicles can only achieve the desired level of structural reliability by restricting the winds through which they are allowed to fly. Measuring the winds just prior to launch and deriving a steering profile that results in lower vehicle loads relative to the measured winds can improve launch availability.

Many launch vehicles use an approach[13-15] where the wind velocity, as a function of altitude, is measured prior to launch—two hours or less is typical—and smoothed (Fig. 1). Figure 1 shows three levels of smoothing; the first two are used with today's launch vehicles. Steering parameters are then developed that will minimize the vehicle's angle of attack relative to the smoothed wind profile. Steering parameters developed in this manner are effective only for the long wavelength components of the wind profile, since they were derived using the smoothed wind. For some launch vehicles, steering parameters are sometimes selected from a library developed prior to the day of launch.

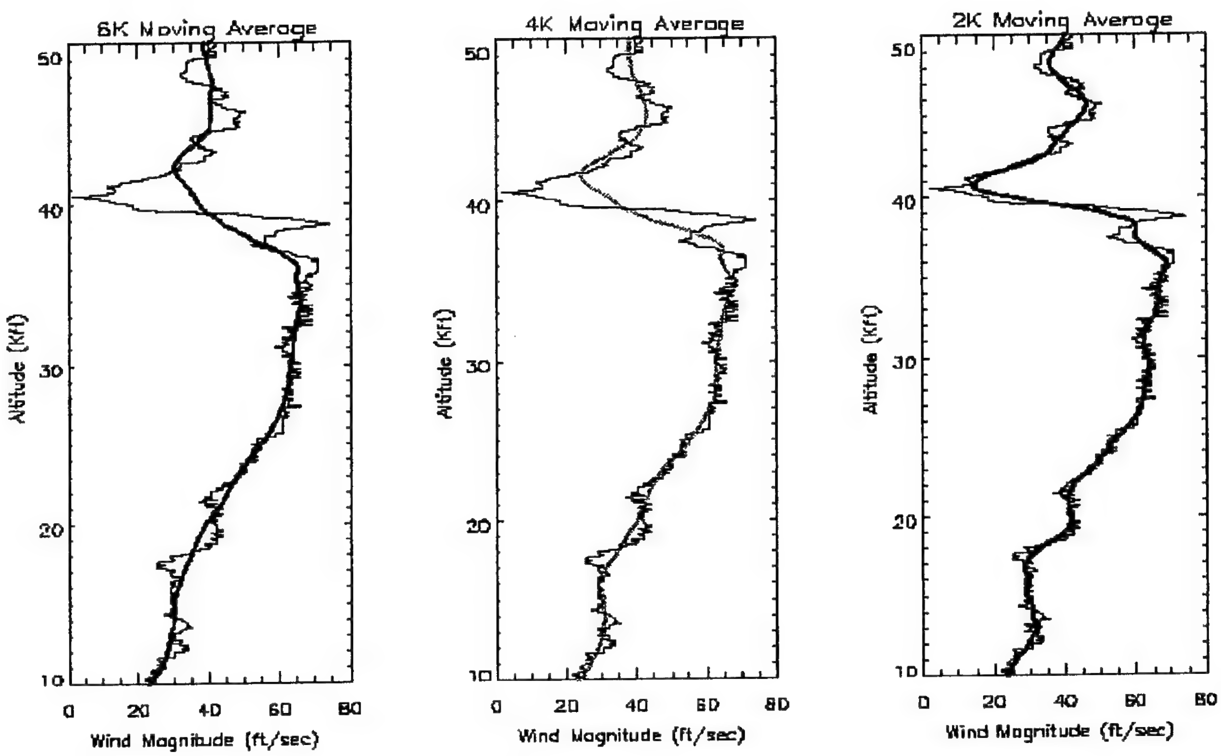

Figure 1. The effect of different levels of wind smoothing is shown. Launch vehicle steering profiles are developed using smoothed wind profiles; the shorter wavelength components are not included. The 6-kft and 4-kft moving averages are typical for launch vehicles today. Loads, however, have to be determined for the complete wind profile, and for any subsequent changes in the wind prior to launch.

After the steering parameters have been established, the launch vehicle is analytically "flown" through the measured winds, and angles of attack and dynamic pressure altitude histories, as well as other parameters, are calculated. These altitude histories are used to establish static-aeroelastic and

other day-of-launch loads, which are then combined with the pre-day-of-launch calculated loads to obtain a predicted total load that represents a desired statistical enclosure.[9,16,17] These enclosure loads are then compared to the vehicle allowable strength values. If the allowable values are exceeded, the vehicle is not flown. If sufficient time is available before the launch window closes, the process of deriving new steering parameters and calculating new loads is repeated. If there is not enough time, the launch attempt is aborted, and the launch vehicle is recycled and prepared for the next available launch window.

Because of the complexity of the phenomenon, atmospheric flight loads are predicted by combining the results of separate and distinct analyses, each of which is performed to predict a different portion of the total load (Refs. 6-10). Attempts are made to minimize excessive conservatism in the manner that the loads from the individual events are combined (Refs. 8, 9, 15, and 17). However, because of how each load contributor is calculated, some overlap between the events will exist. This overlap can lead to an over prediction of the enclosure load, and a reduction in launch availability. Unnecessary launch delays impact mission cost and increased risk to mission success.

Recent work in the areas of atmospheric turbulence/gust loads analysis[18-20] and the determination of the spectral boundary between slowly and rapidly varying wind components[21] has made it possible to develop a refined day-of-launch placard loads analysis procedure. The proposed procedure to be described here reduces the amount of overlap between various load analyses, which should reduce the total predicted load and, therefore, leads to improved launch availability.

2. Load Contributors

Before describing the refined day-of-launch loads analysis approach, the more critical load contributors and the associated analysis procedures will be described. The most critical contributors to day-of-launch loads include static-aeroelastic loading, loading due to atmospheric turbulence/gusts, buffet loads, control system-induced loads, engine thrust loads, and drag loads. In addition, analyses are performed to estimate loads due to items such as wind measurement error, changes in day-of-launch winds from the time they are measured to when the vehicle is actually launched, and vehicle dispersions from the nominal parameters used in the analyses.

2.1 Static-Aeroelastic Loads

Typically, static-aeroelastic load analyses are performed to establish loads due to the portion of the vehicle's angle of attack that varies relatively slowly with time. This change in angle of attack includes effects of the day-of-launch winds. An inherent assumption is that the change in angle of attack is slow relative to the periods of vibration of the launch vehicle/space vehicle system and, therefore, elastic mode dynamic amplification effects do not need to be included in the analysis.

Rigid body translation and rotation accelerations are included. However, in some cases the rotation acceleration effects are established separately, and then combined with the static-aeroelastic analysis loads. The static-aeroelastic analysis needs to include aeroelastic effects, drag, engine thrust, and engine side forces. If the vehicle is large enough, and deflects sufficiently, beam-column effects should also be included.

With existing procedures, steering parameters are derived for a smoothed wind profile. However, the raw wind profiles are used in predicting the launch vehicle's flight response altitude histories (angles of attack, rigid body accelerations, dynamic pressure, etc.) that are used to establish the static-aeroelastic loads. There are two primary drawbacks to this approach. First, the raw wind profiles contain short wavelength components that are not persistent (Ref. 21). Therefore, the portion of the total static-aeroelastic load due to these non-persistent components cannot be considered valid for when the vehicle flies through the wind at some future time. The loads experienced by the actual vehicle could be higher, or they could be lower, depending on how the wind changes. Secondly, the short wavelength components of the wind will excite the lower elastic modes of vibration of medium and heavy lift launch vehicles. Current static-aeroelastic analysis procedures do not account for these effects.

2.2 Lack-of-Wind-Persistence Load

The change in static-aeroelastic load due to the change in the wind from the time it is measured to the time the vehicle is launched must be considered.[7,14,22] This change in load is typically obtained by analytically flying the vehicle through pairs of historical wind profiles and calculating the static-aeroelastic load as a function of altitude for each wind. The changes in load from the first wind profile to the second is then computed. Sufficient pairs are included to allow for a statistical description of change in load as a function of time between wind pairs and altitude. This pre-day-of-launch, lack-of-wind-persistence load is then combined on the day of launch with the static-aeroelastic and other loads.

2.3 Turbulence/Gust Loads

Gust loads analyses are performed to establish launch and space vehicle loads caused by the short wavelength, relatively short-duration components of the wind that might be encountered during atmospheric flight. In some day-of-launch load analysis approaches, the gust analysis is assumed to also make up for the lack of elastic-mode, dynamic-amplification effects in the static-aeroelastic load analysis.

In most gust analyses, the launch vehicle is instantaneously enveloped by a synthetic gust velocity profile, which, in effect, is a time-dependent modulation of the local angles of attack along the length of the vehicle. The amplitude, wavelength, and shape of the gusts are selected such as to induce loads that are equivalent to a desired level of statistical conservatism. In Ref. 18, several synthetic gust approaches are described in more detail, and a new Monte Carlo approach is introduced that uses forcing functions derived by extracting the turbulent, short-duration components of the wind from measured wind profiles.

To establish proper loads, a gust load analysis must include aeroelastic stiffness and damping effects, as well as the launch vehicle control system-induced engine side forces. The control system simulation is required to obtain the proper rigid body response of the vehicle, which will also couple with the elastic modes through the aerodynamic stiffness and damping.

A gust load analysis simulation can establish static-aeroelastic loads. However, a static-aeroelastic load analysis cannot yield proper gust loads, since the elastic-mode, dynamic-amplification effects are not included. A gust load analysis is more accurate than current static-aeroelastic atmospheric flight load analysis procedures for flight times for which stationary vehicle properties can be assumed.

2.4 Other Load Contributors

Other load contributors that are included in day-of-launch load placard calculations include loads due to buffet excitation and control system-induced loads (Refs. 5-8). In addition, other analyses are performed to estimate loads due to items such as wind measurement error and vehicle dispersions from the nominal parameters used in the analyses. Although these contributors can amount to a significant portion of the enclosure load, this paper will concentrate on the relationship between the static-aeroelastic load (day-of-launch wind load), the lack-of-wind-persistence load, and the load due to turbulence/gust.

3. Day-of-Launch Loads Combination

Because atmospheric flight load contributors are calculated in separate analyses, and at least one is a function of the day-of-launch winds, the enclosure load has to be established by statistically combining these contributors on the day of launch. There are various techniques for combining the different load contributors (Refs. 9, 10, 16, and 17). The procedures that are based on the Central Limit theorem are probably the most technically defensible.

The magnitudes of the loads to be combined depend on a number of considerations. The magnitude of the static-aeroelastic load will vary as a function of the steering parameters and the latest measured wind profile for which loads can be determined prior to launch. Once steering parameters have been established for a particular wind profile, the static-aeroelastic loads will tend to increase—although not always—for subsequent wind profiles, since the wind will change and the steering will no longer be optimum. The lack-of-wind-persistence loads will vary as a function of time between when the wind is measured and the vehicle is expected to launch. Currently, the gust load is calculated prior to the day of launch and, therefore, does not change on the day of launch. The buffet and other load contributors also do not change on the day of launch. These loads will, however, vary as a function of altitude and other parameters such as Mach number.

4. Proposed Procedure

The concept behind the proposed procedure is best illustrated with the aid of Fig. 2. Figure 2(a) shows a typical wind profile. This profile is composed of two components, shown in Figs. 2(b) and 2(c). Figure 2(b) shows the longer, vertical wavelength features [also superimposed in Fig. 2(a)], and Fig. 2(c) shows the shorter wavelength components. It is intuitive that the longer wavelength components will change more slowly over time than the shorter, more turbulent components. Since the rapidly-varying components do not persist, loads induced by these turbulent features must be established statistically. Once accounted for statistically, however, these wind features can then be excluded from the measured wind used in the static-aeroelastic load analyses performed just prior to launch.

Reference 21 demonstrates that the average spectral boundary between the slowly-varying portion of wind profiles and the more rapidly-varying, turbulent components, can be determined. This boundary (Fig. 3) is a function of the time between when a wind is measured and the launch. The longer the time period, the longer the wavelengths that must be considered turbulent. This concept is illustrated in Figs. 2(c), 2(f) and 2(i). Figure 2(c) shows the components of the wind that have to be considered turbulent if the launch vehicle flies through this wind one hour after it is measured. Figure 2(f) shows the components of the same wind that have to be treated as turbulent if the vehicle flies through it 45 minutes after measurement, and Fig. 2(i) shows the turbulent components for a 30-minute time period. An observable change in each wind is highlighted by the dotted boxes. As one goes from the 60-minute wind [Fig. 2(c)] to the 30-minute wind [Fig. 2(i)], the magnitude of the turbulent components decreases. Since the total wind needs to remain the same, any reduction in the turbulent components must be matched by an increase in the slowly-varying components , which can be seen in the dotted boxes in Figs. 2(b), 2(e) and 2(h).

Since the turbulent component varies relatively rapidly, any loads predictions associated with it on the day of launch become invalid for some time point removed from the measured profile time. In some cases, the predicted loads would be conservative, and in other cases the loads would be under predicted. Therefore, the loads due to the turbulent components of the wind must be treated statistically.

The gust analysis has historically served the purpose of establishing loads due to atmospheric turbulence. Therefore, if the gust analysis accounts statistically for the rapidly-varying components, then these components do not need to be included in the wind profiles used in the day-of-launch wind load analyses. In addition, these rapidly-varying components do not need to be included in the lack-of-wind-persistence load analyses either, since these loads are included to account for the change, over time, in the loads due to the slowly-varying components of the day-of-launch winds.

As a result, the wind profiles used in the load analyses performed just prior to launch can be filtered to remove the turbulent components. The wavelength at which the measured wind profile can be filtered will depend on the time between when the wind is measured and the time when the launch vehicle is expected to fly through the wind. The longer the time, the longer the wavelengths that have to be removed, and the larger the corresponding statistical turbulence/gust load (Ref. 18) will be that has to be added to the day-of-launch wind load obtained with the filtered wind. In a practical application, some spectral overlap should be kept between the slowly-varying components and those that are removed because they are turbulent (Refs. 19 and 21).

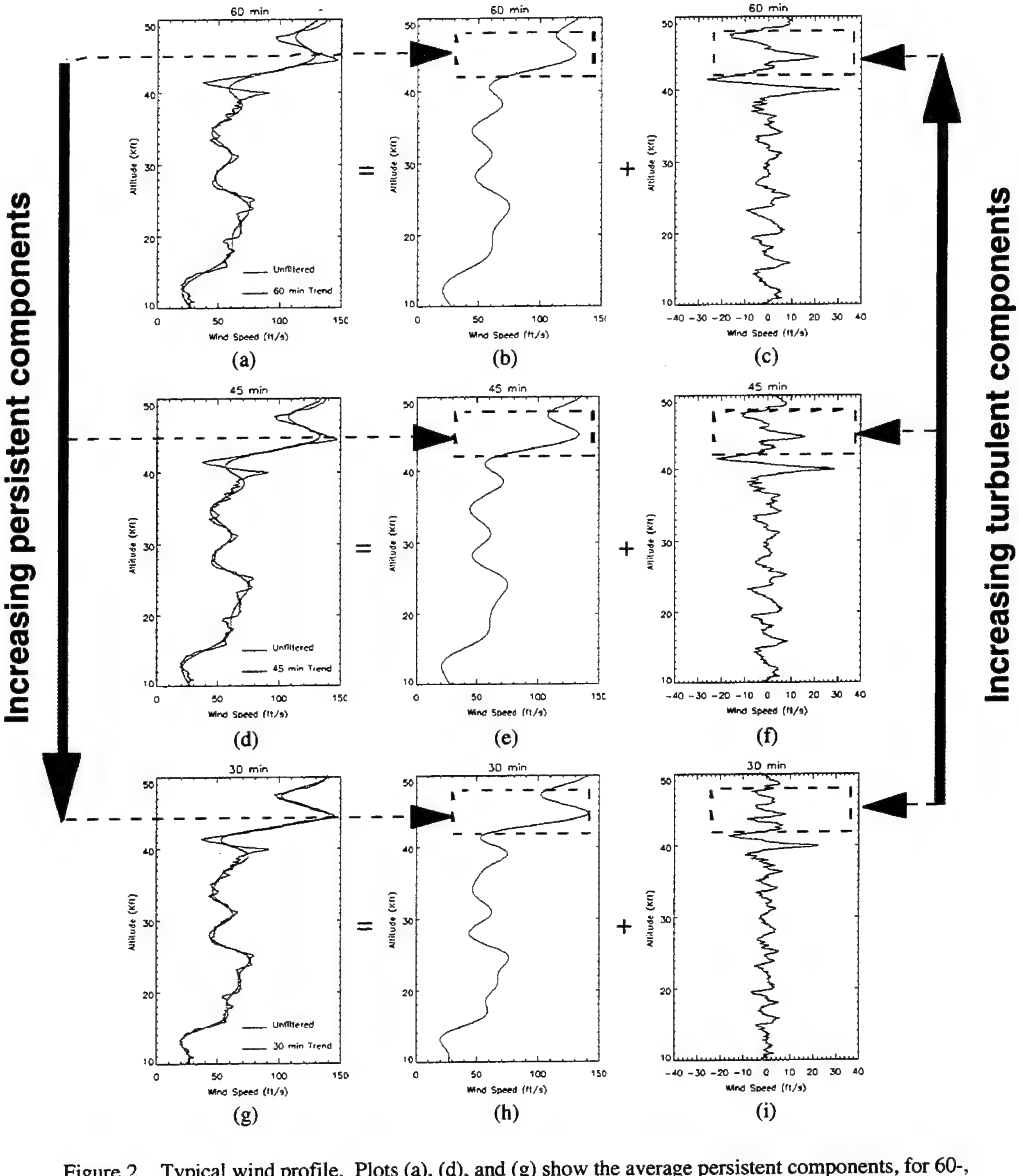

Figure 2. Typical wind profile. Plots (a), (d), and (g) show the average persistent components, for 60-, 45-, and 30-minute time periods, superimposed on the measured profile. Plots (b), (e), and (h) show the slowly varying components, and (c), (f), and (i) show the corresponding turbulent components.

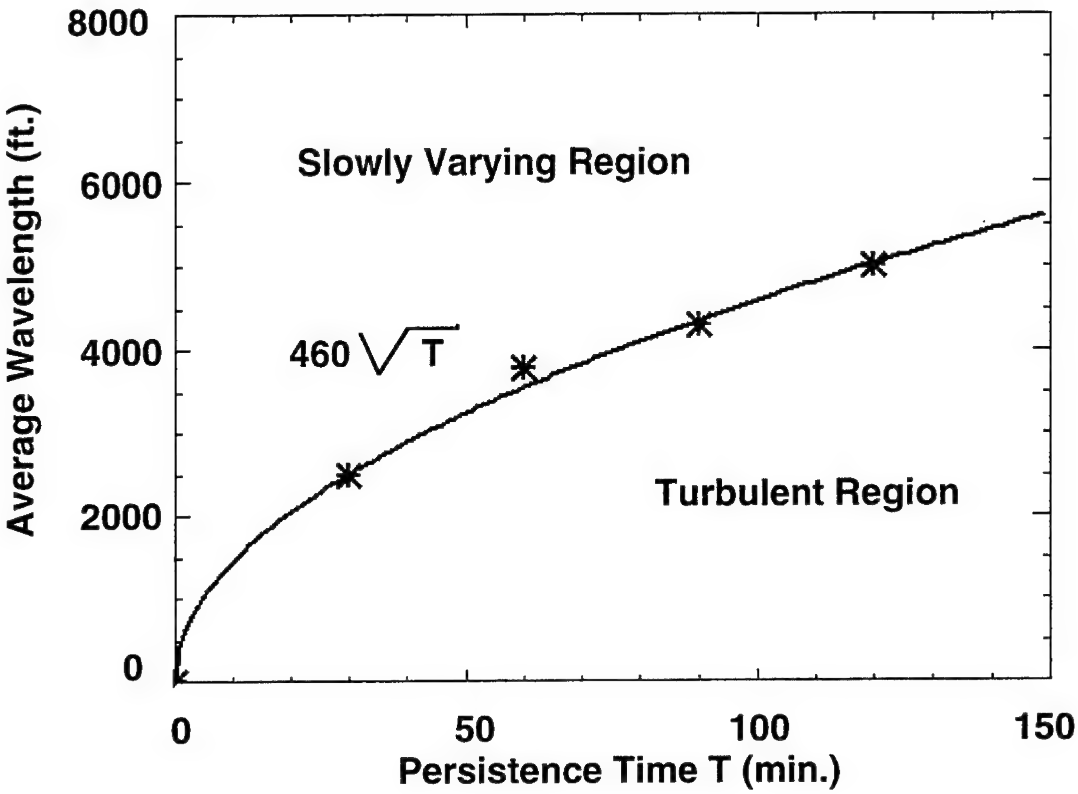

Figure 3. Average wavelength boundary between relatively slowly-varying components of wind profiles and more rapidly-varying, turbulent components (Ref. 21).

4.1 Proposed Procedure - Implementation

The proposed procedure relies on a consistent treatment of the variousa day-of-launch load contributors. The calculation and implementation of the turbulence/gust, lack-of-wind-persistence, and day-of-launch wind loads, as required for the proposed procedure, will be described in more detail.

4.1.1 Turbulence/Gust Loads

References 18-20 present a new Monte Carlo turbulence/gust load analysis approach that defines turbulence/gust loads in a consistent manner relative to the proposed filtering of the winds on the day-of-launch. Reference 19 presents the methodology for developing altitude-consistent gust forcing functions for selected lack-of-wind-persistence time periods. The forcing functions are generated by high-pass filtering historical wind profiles, and then extracting from the resulting profiles altitude-consistent segments. These segments are then used in Monte Carlo load analyses (Refs. 18, 20) to define gust loads that are a function of both altitude and time remaining to launch.

Time periods for which forcing functions and gust loads have been developed include 30, 45, 60 and 90 minutes. As expected, and indicated in Ref. 18, gust loads increase as the time period to launch increases. This change in loads appears to be relatively smooth and, thus, it should be possible to interpolate for time points between those for which forcing functions and loads have been developed.

4.1.2 Lack-of-Wind-Persistence Loads

Lack-of-wind-persistence loads need to be established with wind pairs that have been low-pass filtered with cutoff wave numbers (frequencies) that encompass those that will be used in the day-of-launch wind load analyses. Experience indicates that 30-, 45-, 60- and 90-minute wind pairs will produce relatively smooth functions that can be used to establish lack-of-wind-persistence loads that correspond to all static-aeroelastic analysis time points within 90 minutes of launch. It should be noted, however, whereas the wavelength cutoff values for the turbulence/gust analysis should be selected to be above the boundary curve presented in Fig. 3, the lack-of-wind-persistence and day-of-launch wind load analyses values should be at, or below, the curve. This overlap in the spectral content is required because the boundary function in Fig. 3 represents average values.

4.1.3 Day-of-Launch Wind Loads

To obtain the full benefit of the proposed approach, wind loads calculated just prior to launch should be established using parameters derived with measured wind profiles that have been low-pass filtered. The wave numbers at which the profiles need to be filtered will depend on the time from the wind measurement to the time the launch vehicle is expected to launch. Calculation of the day-of-launch wind loads would then proceed as with current procedures. Test problems to date confirm the expectation that on the average, lower loads will result.

It should be noted, however, that the more frequency content is retained in the day-of-launch wind profile, the more likely it becomes that a static-aeroelastic load analysis will not yield appropriate loads. Therefore, there is a limit beyond which one cannot move the frequency content from the turbulence/gust load analysis to the day-of-launch wind load analysis, unless one is willing to include elastic mode dynamic amplification effects in the day-of-launch wind load analyses, and the corresponding lack-of-wind-persistence load analyses.

4.1.4 Day-of-Launch Loads Combination

The day-of-launch loads combination can generally proceed as with current procedures. The primary difference will be the use of turbulence/gust loads that are dependent on altitude and the filter levels (i.e., time to launch) used on the day-of-launch winds. For example, if the wind profile is

measured 45 minutes before the expected launch time and, thus, low-pass filtered at a wave number of 1/(3086 ft), then the turbulence/gust loads that should be combined with this day-of-launch wind load would need to have been calculated with the corresponding 45-minute, high-pass filtered turbulence forcing functions. A cutoff wave number of 1/(4200 ft), which includes the previously discussed spectral overlap, would have been appropriate for deriving the turbulence/gust forcing functions. Also, the lack-of-wind-persistence load should have been calculated with wind pairs that were low-pass filtered at the same wave number as used for the day-of-launch wind load analysis; i.e., 1/(3086 ft).

4.2 Proposed Procedure – Example

Critical aspects of the proposed procedure were analyzed on a heavy lift launch vehicle that recently launched its payload successfully. Atmospheric flight loads were calculated for several altitude bands of the Eastern Range of the United States. The load analyses were first performed using the procedures that were used during the actual launch of the vehicle; we will refer to these loads as the "Existing Procedure" loads. The analyses were then repeated with the static-aeroelastic and turbulence/gust loads calculated as proposed herein. The lack-of-wind-persistence loads were estimated, based on the changes in the static-aeroelastic load between the existing and proposed approaches. The buffet and dispersion loads were assumed to be the same for both approaches.

The gust loads for the proposed procedure were established in Ref. 18, using the new Monte Carlo approach. The loads were calculated for 30-, 45-, and 60-minute time periods. For the example presented herein, the 90-minute gust loads were estimated from the gust loads from the three shorter time periods. The resulting 90-minute loads are consistent with those obtained for another launch vehicle for which Monte Carlo gust loads were established with 90-minute forcing functions. The gust loads used with the existing procedure during the actual launch were derived with the 1-cosine synthetic gust analysis approach, with a 30 ft/sec gust magnitude.

The static-aeroelastic loads for the proposed procedure were derived as with the existing procedure, except that the wind profiles that were used were low-pass filtered to be consistent with the 90-, 60- and 30-minute turbulence/gust loads. The steering parameters used in the flight simulations were derived with a wind measured prior to the 90-minute balloon. Therefore, for the existing procedure, any changes in static-aeroelastic load from one wind measurement to the next were caused by changes in the wind. For the proposed procedure, in addition to the changes in the wind, the low-pass filter levels were also changed according to the function presented in Fig. 3.

In Table 1 the various load contributors obtained, at a flight altitude of 38,000 ft, with the existing approach are compared to the loads obtained with the new, proposed approach. All load values in the table were normalized relative to the largest value, which was the 60-minute total load for the existing procedure. As can be seen, the proposed approach yields lower overall loads for each time period. For the 60-minute calculation, the proposed procedure yields total combined loads that are 9 percent lower, and for the 30-minute results, the proposed procedure provides loads that are 16 percent lower. Experience indicates that total load reductions of this magnitude will result in substantial increases in launch availability.

Table 1. Comparison of Loads at Flight Altitude of 38,000 ft

Load	**30 min**	**60 min**	**90 min**
	Existing Procedure		
STEL	0.06	0.11	0.09
WP	0.26	0.31	0.35
Gust	0.29	0.29	0.29
Buffet	0.08	0.08	0.08
Other	0.18	0.21	0.18
Total	**0.87**	**1.00**	**0.99**
	Proposed Procedure		
STEL	0.06	0.09	0.05
WP	0.21	0.25	0.29
Gust	0.20	0.28	0.33
Buffet	0.08	0.08	0.08
Other	0.18	0.21	0.18
Total	**0.73**	**0.91**	**0.93**

5. Practical Considerations

References 18-21, and the example problem presented herein, have demonstrated the feasibility of the analyses needed for the proposed approach. However, for each launch vehicle, separate studies should be performed to determine the shortest lack-of-persistence time for which valid turbulence/gust, lack-of-wind-persistence, and day-of-launch filtered wind loads can be established.

5.1 Elastic Mode Dynamic Amplification

Since the turbulence/gust analysis is a statistical prediction of enclosure loads, it will generally be more conservative than a load based on a measured day-of-launch wind profile. Therefore, there is significant advantage to measuring a wind profile as close to launch as possible. However, the closer to launch, the more likely that the day-of-launch wind load analysis will have to consider the launch vehicle/space vehicle elastic modes of vibration, which are not considered in typical static-aeroelastic analyses. If the elastic modes of vibration cannot be included, then the portion (frequency content) of the wind profile that excites the elastic modes of vibration, needs to be retained in the turbulence/gust loads analysis.

5.2 Wind Measurement Limitations

If a balloon system[14,22,23-25] is used, because of its relatively slow rise rate, one must make assumptions about how to correlate the lack-of-persistence time to the balloon rise rate. For some launch vehicles, this is taken at only one point, the maximum dynamic pressure time of flight. Therefore, the lack-of-wind-persistence loads for altitudes below and above this value will be larger, and must be accounted for in the analyses.

For a Doppler Radar System,[26] one must consider wavelength resolution constraints, which will limit the frequency content of the wind profile. This, in turn, will limit reductions in the pre-day-of-launch turbulence/gust loads that are achievable as one gets closer to launch time with the wind measurements. Indications are that 30-minute lack-of-wind-persistence times are achievable. For wind profiles measured closer to launch than 30 minutes, reduction in the corresponding turbulence/gust loads is less certain; however, this requires more study. Reductions in lack-of-wind-persistence load should continue to accrue because of the reduction in the time from wind measurement to when the vehicle is expected to fly through the wind. This reduction in load, however, might be partially offset by the fact that shorter duration wind features will have to be retained in the lack-of-wind-persistence analyses to be consistent with the static-aeroelastic load analyses.

6. Conclusions

An atmospheric flight load analysis approach that treats the relationship between the turbulence/gust load and the day-of-launch wind load analyses in a consistent manner has been presented. The procedure takes advantage of the recently-developed ability to separate the slowly-varying wind components from the more rapidly-changing turbulent features, and a new Monte Carlo gust loads analysis methodology that results in a statistical description of gust loads that are a function of altitude and time to launch. By removing from measured day-of-launch winds the turbulent components, the overall day-of-launch wind loads will decrease. The removed features will have been properly accounted for by the turbulence/gust load analysis that uses forcing functions developed from the turbulent features of historical, measured wind profiles. Various aspects of the proposed procedure were implemented on a heavy lift launch vehicle, and the results indicate substantial reductions in overall predicted flight loads.

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